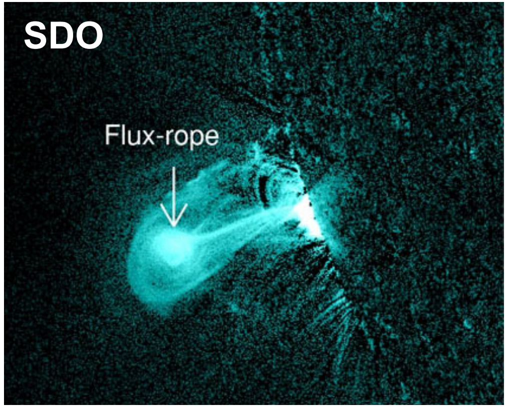
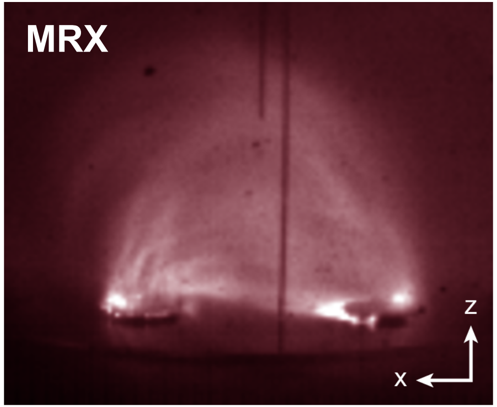
Laboratory identification of MHD eruption criteria in the solar corona



Clayton E. Myers
November 20, 2015



MRX Collaborators: M. Yamada, H. Ji, J. Yoo, W. Fox, and J. Jara-Almonte
CfA/SAO Collaborators: A. S. Savcheva and E. E. DeLuca
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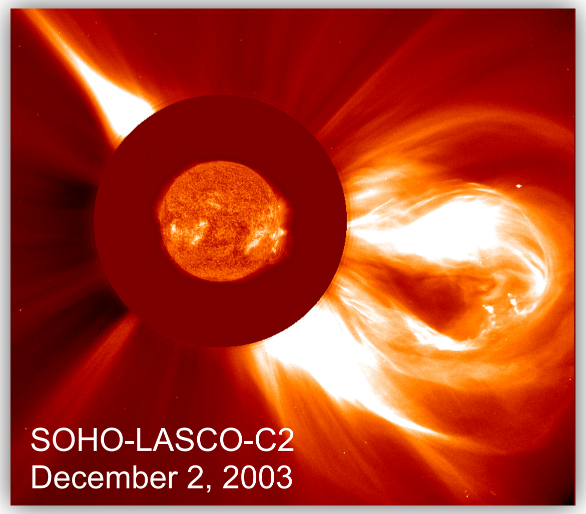
Presentation overview

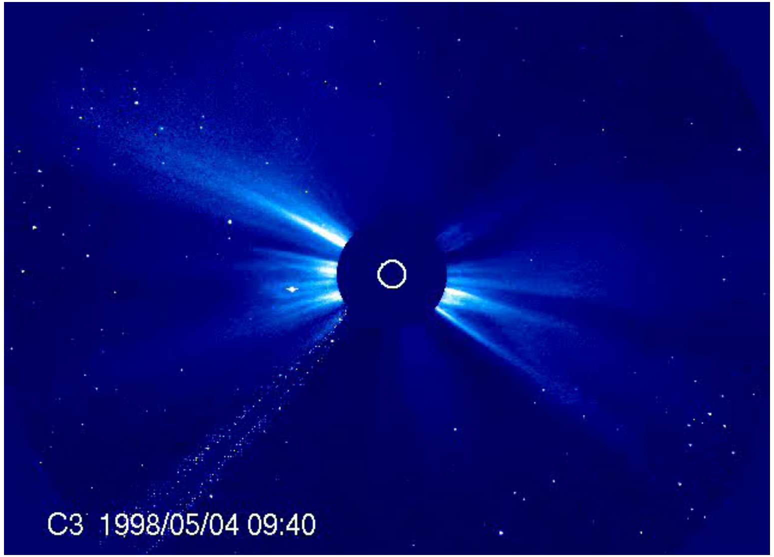
- **Objective:** Study candidate storage-and-release solar eruption mechanisms in the laboratory
- **Approach:** Design and build a laboratory experiment to generate long-lived line-tied magnetic flux ropes

  Key diagnostics: *in situ* magnetic probes
- **Major Results:**
  1. Experimental mapping of the torus vs. kink instability parameter space
     → four distinct stability regimes identified
  2. The toroidal field tension force is dominant in certain regimes
     → a restraining force that can lead to failed eruptions
- **Accepted for publication in *Nature* (Myers et al., 2015)**

Motivation: Coronal Mass Ejections (CMEs)

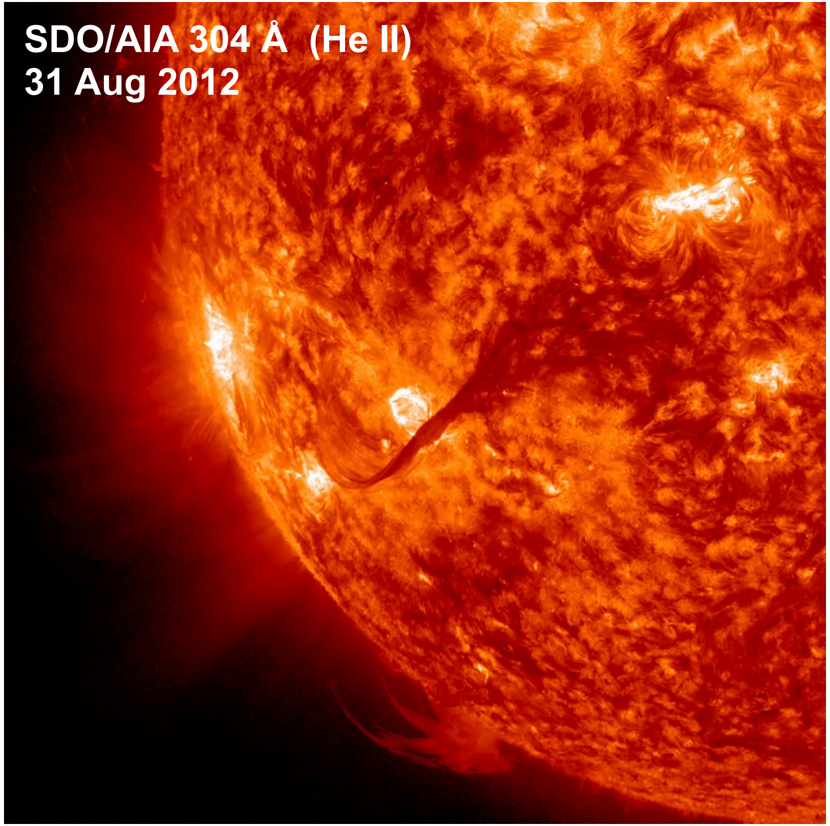
- Large-scale ejections of particles and magnetic field (~500 km/s)
- Often associated with solar flares (no causal relationship)





- CMEs are the primary driver of space weather
- The mechanisms that initiate and drive CMEs are not well understood

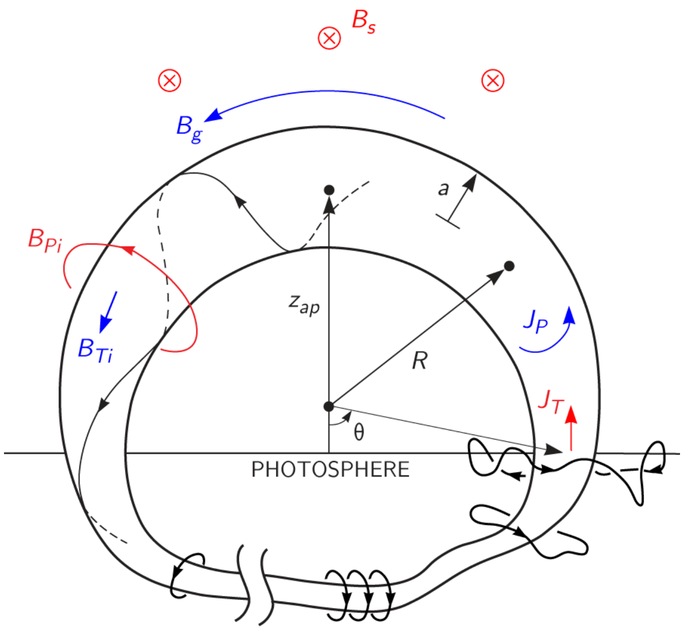
The storage and release solar eruption paradigm



- Magnetic energy is transferred very slowly into the corona (days to weeks)
  → "storage" phase
- Eruptions occur on a much faster timescale (minutes to hours)
  → "release" phase
- How is energy stored in the corona?
  - Coronal plasma currents
  - Magnetic flux ropes
- What triggers an eruption?
  - Magnetic reconnection
  - Ideal MHD instabilities

Fields and forces in a line-tied magnetic flux rope

- Primary magnetic field components:
  - External "guide" field B_g (vacuum)
  - External "strapping" field B_s (vacuum)
  - Internal poloidal field B_{Pi} (plasma)
  - Internal toroidal field B_{Ti} (plasma)
- At low-β, **J×B** forces dominate:
  - Poloidal hoop force: $f_h = +J_T \times B_{Pi}$
  - Strapping field force: $f_s = -J_T \times B_s$
  - Toroidal field forces: $f_T = -J_P \times (B_g + B_{Ti})$



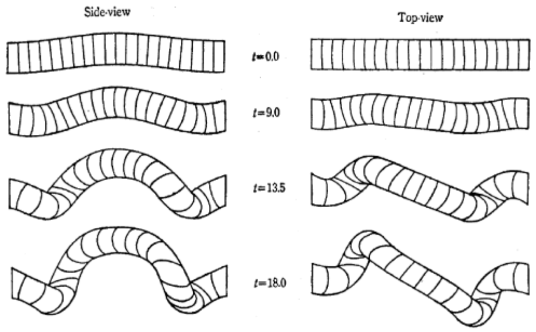
Adapted from J. Chen, *ApJ*, 1989, 2010

Eruption mechanisms: the kink instability

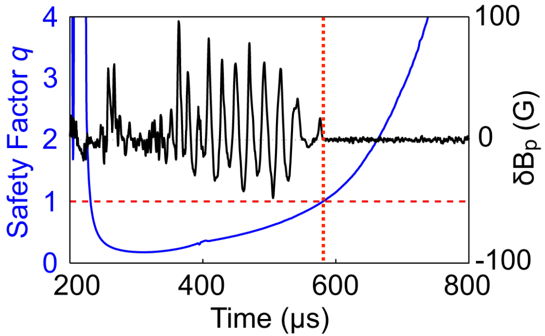
- The kink instability has long been studied as a possible driver of solar eruptions [Gold & Hoyle, 1960]
- The kink instability is current driven: competition between stabilizing toroidal field and destabilizing poloidal field
- The edge safety factor:

$$q_a = q(a) = \frac{2\pi a}{L}\frac{B_g}{B_{Pa}} \lesssim 1$$

$$a \equiv \text{minor radius}$$
$$L \equiv \text{flux rope length}$$
$$B_g \equiv \text{guide field}$$
$$B_{Pa} \equiv \text{edge poloidal field}$$



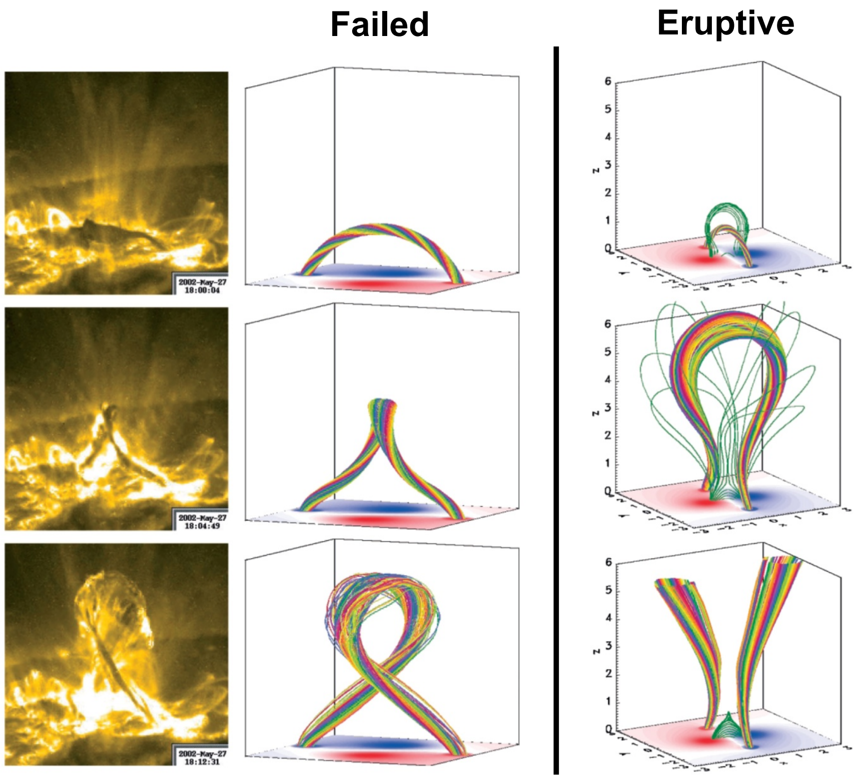
Sakurai, 1976



E. Oz, C. E. Myers, M. Yamada, et al., *Phys. Plasmas* **18**, 102107 (2011)

Eruption mechanisms: the torus instability

- “Loss of equilibrium”
- Hoop forces slowly drive the flux rope to expand
- Strapping forces hold the flux rope in equilibrium
- The strapping field decays with height
- A point is reached where the strapping force is too weak to hold down the rope



Török & Kliem, *ApJ*, 2005

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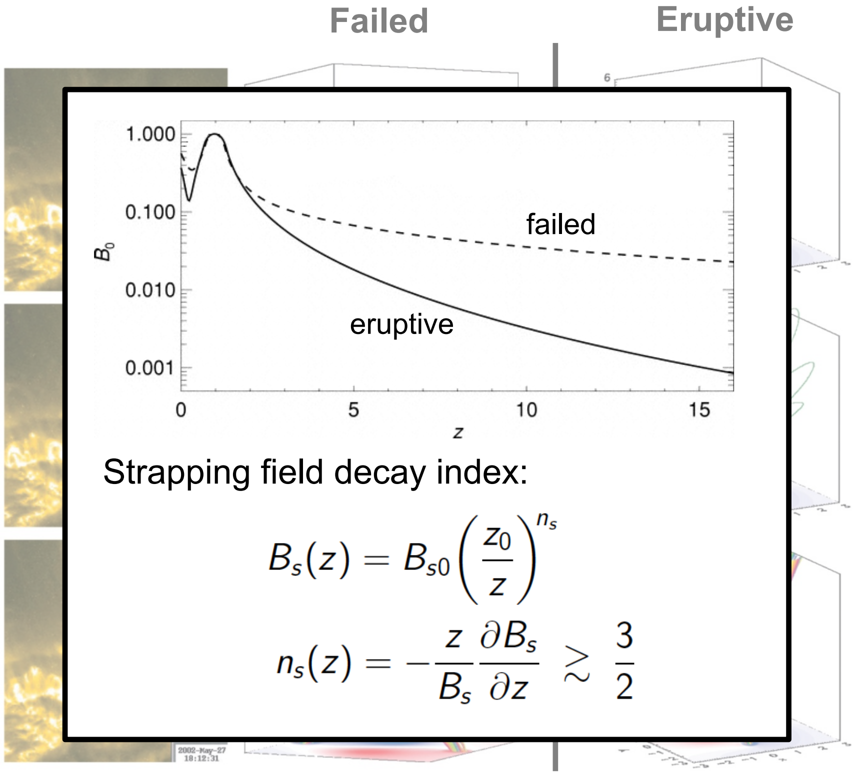


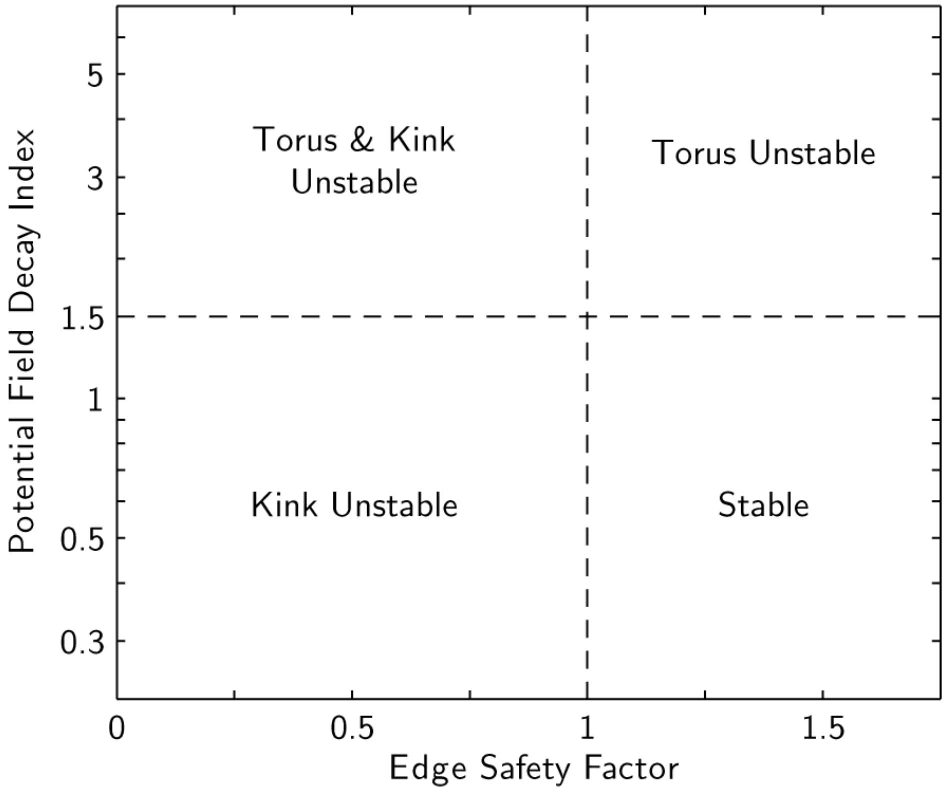
Strapping field decay index:

$$B_s(z) = B_{s0}\left(\frac{z_0}{z}\right)^{n_s}$$

$$n_s(z) = -\frac{z}{B_s}\frac{\partial B_s}{\partial z} \gtrsim \frac{3}{2}$$

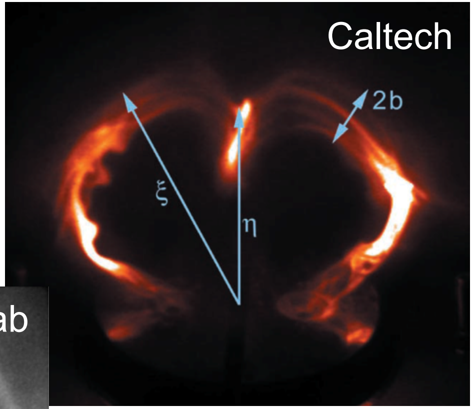
Török & Kliem, *ApJ*, 2005

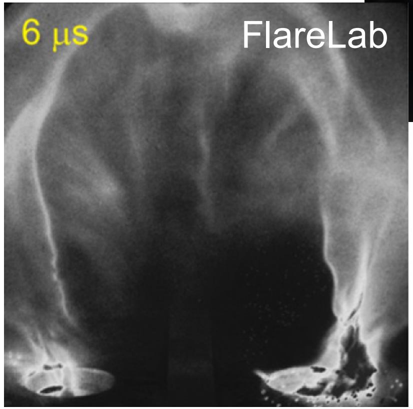
The anticipated torus vs. kink instability parameter space

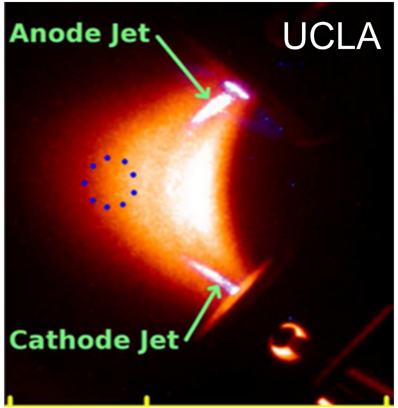


Previous laboratory flux rope experiments

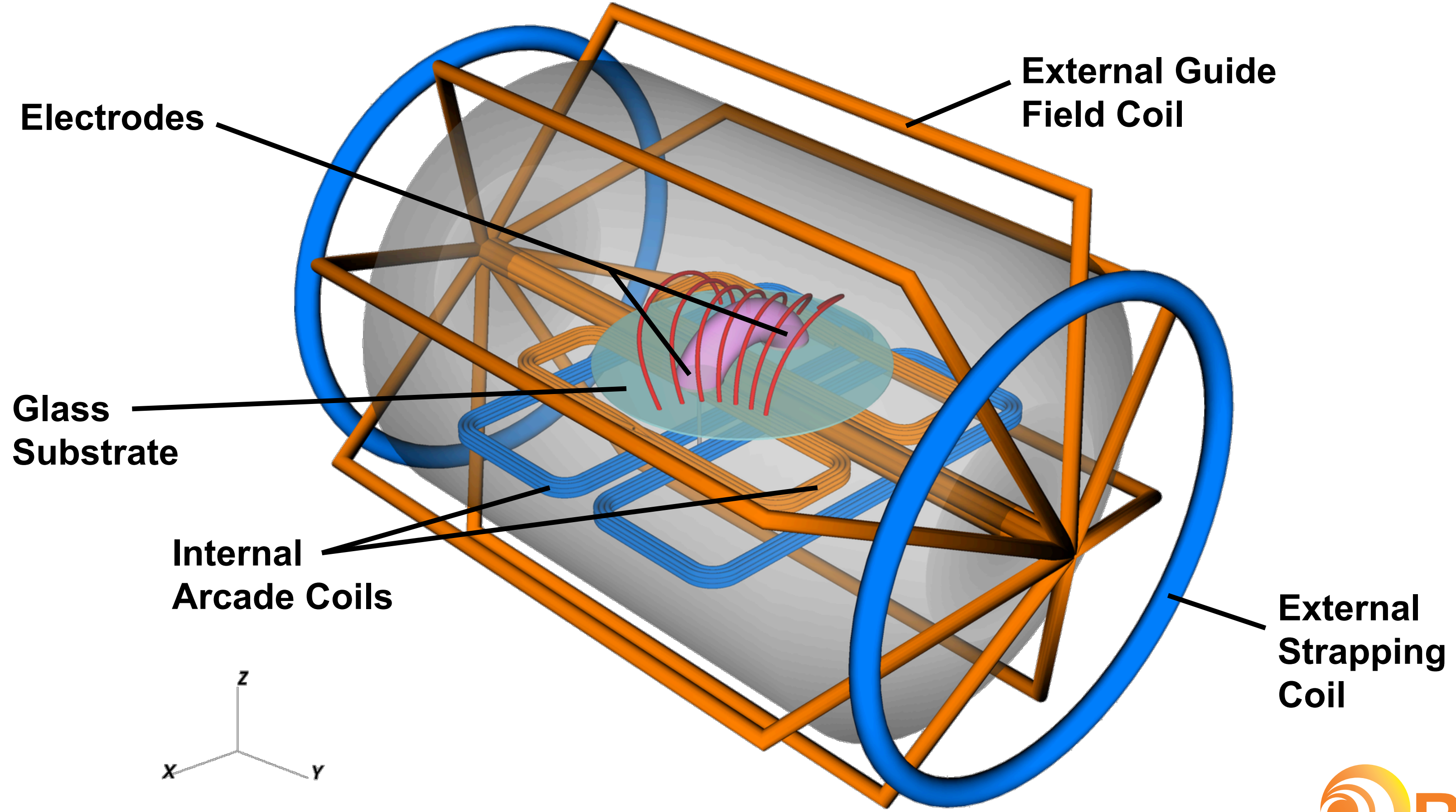
- Several existing experiments have studied flux rope eruptions
- Caltech & FlareLab dynamically inject magnetic flux at the footpoints
- UCLA uses lasers to dynamically inject mass and current at the footpoints
- These eruptions are externally triggered (not storage-and-release)







Line-tied magnetic flux rope experiments in MRX



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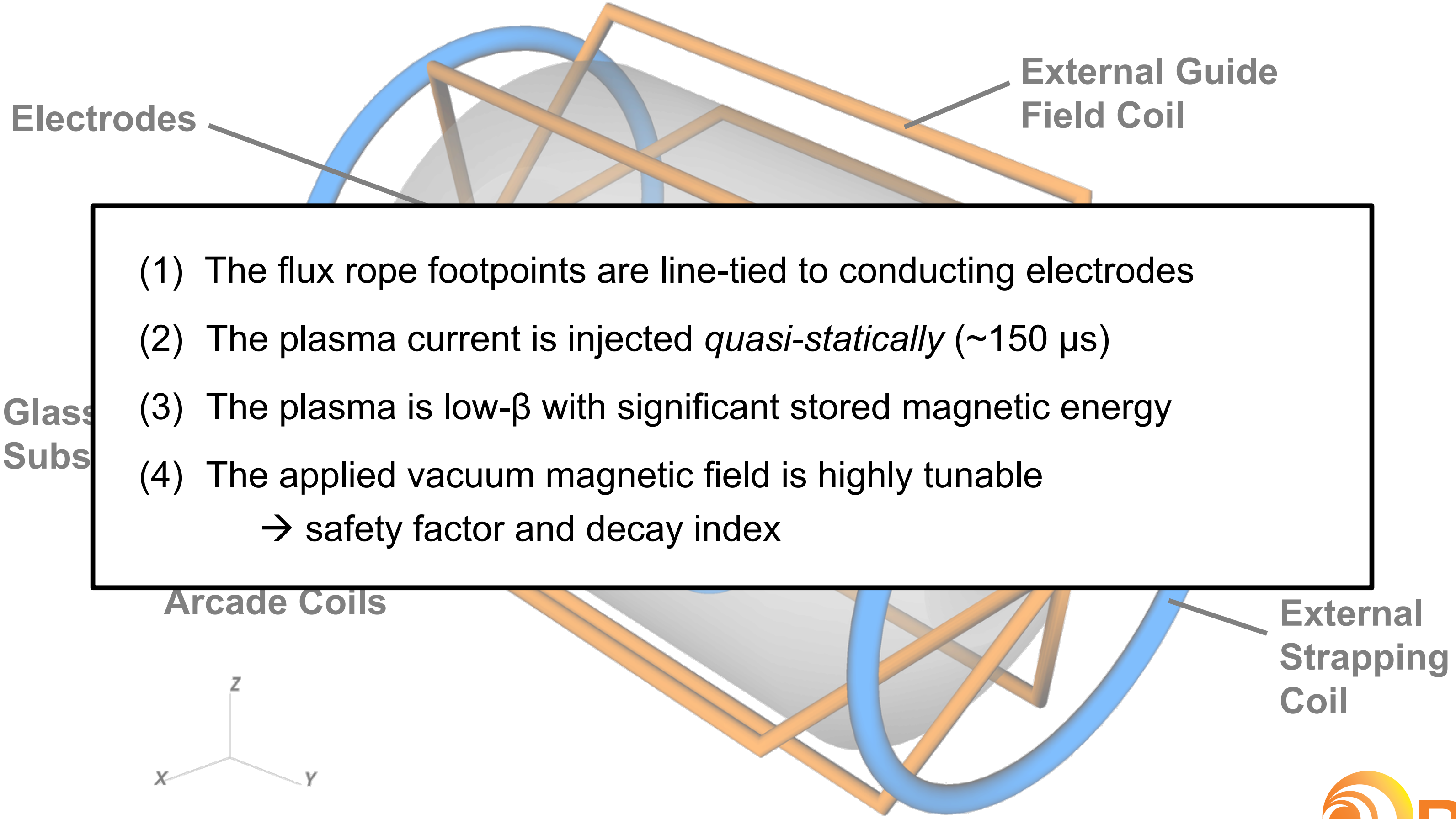


(1) The flux rope footpoints are line-tied to conducting electrodes

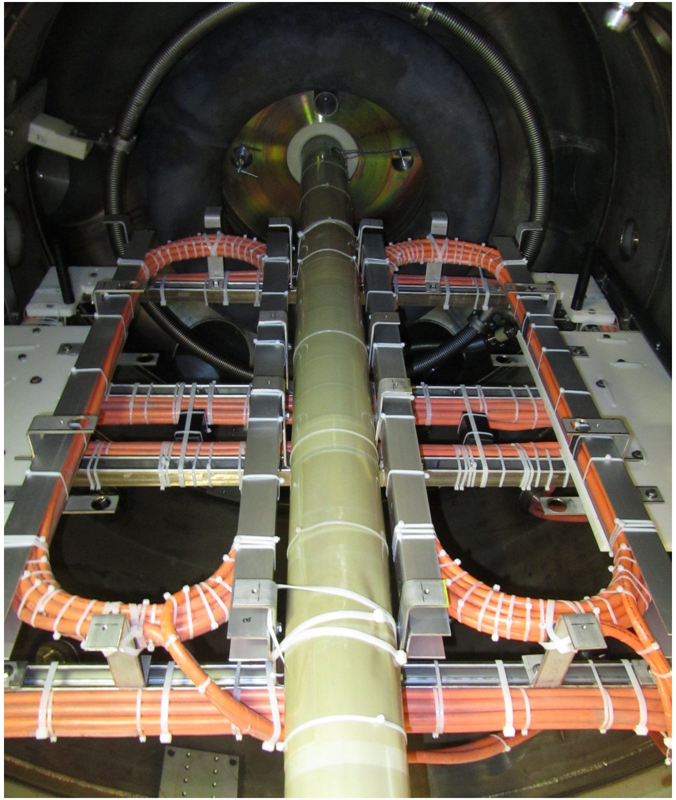
(2) The plasma current is injected *quasi-statically* (~150 μs)

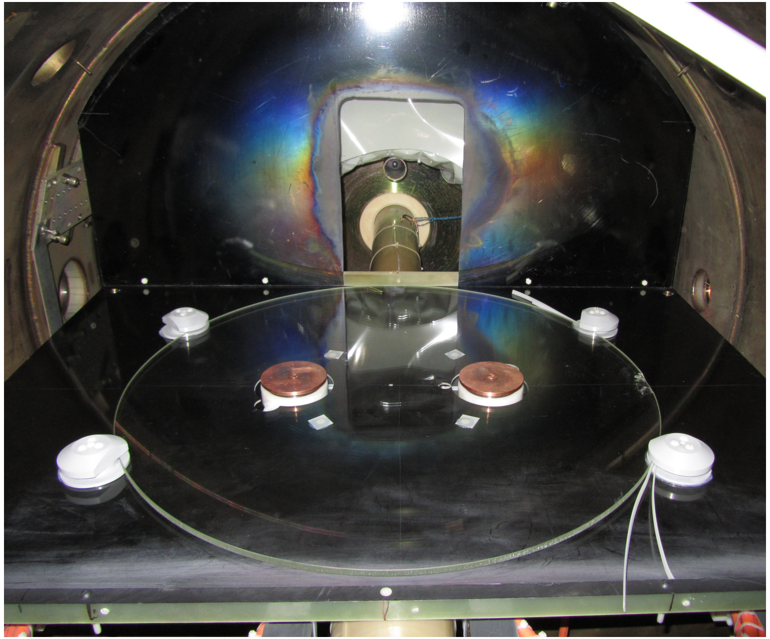
(3) The plasma is low-β with significant stored magnetic energy

(4) The applied vacuum magnetic field is highly tunable

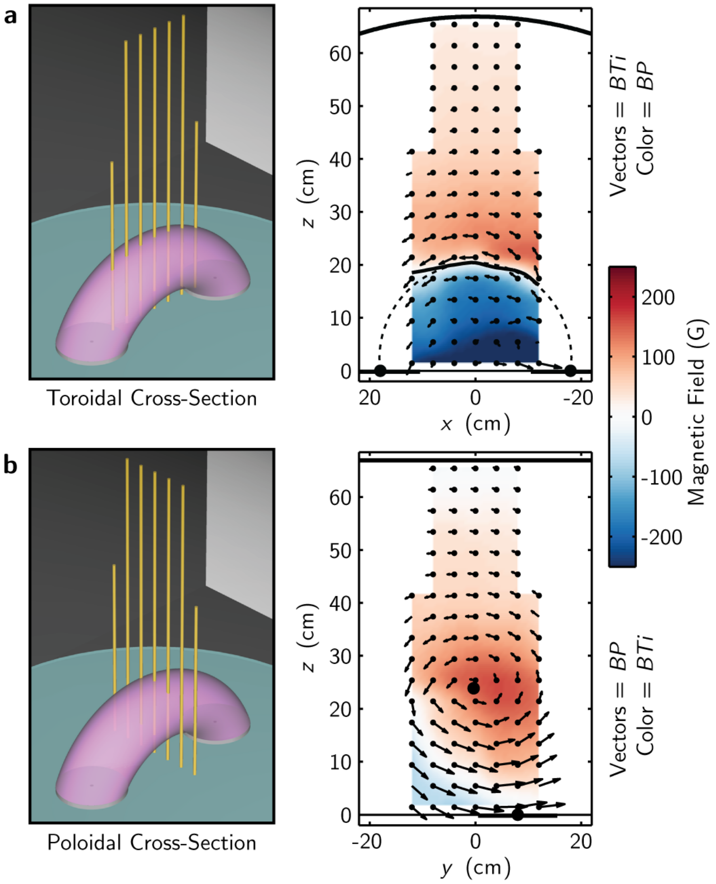
→ safety factor and decay index

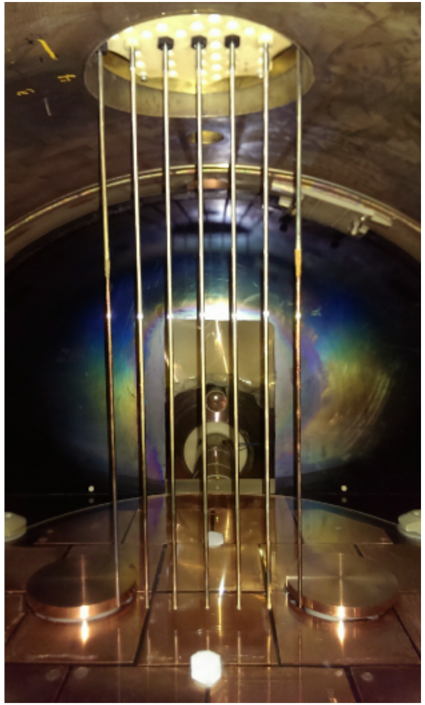
The experimental apparatus as installed



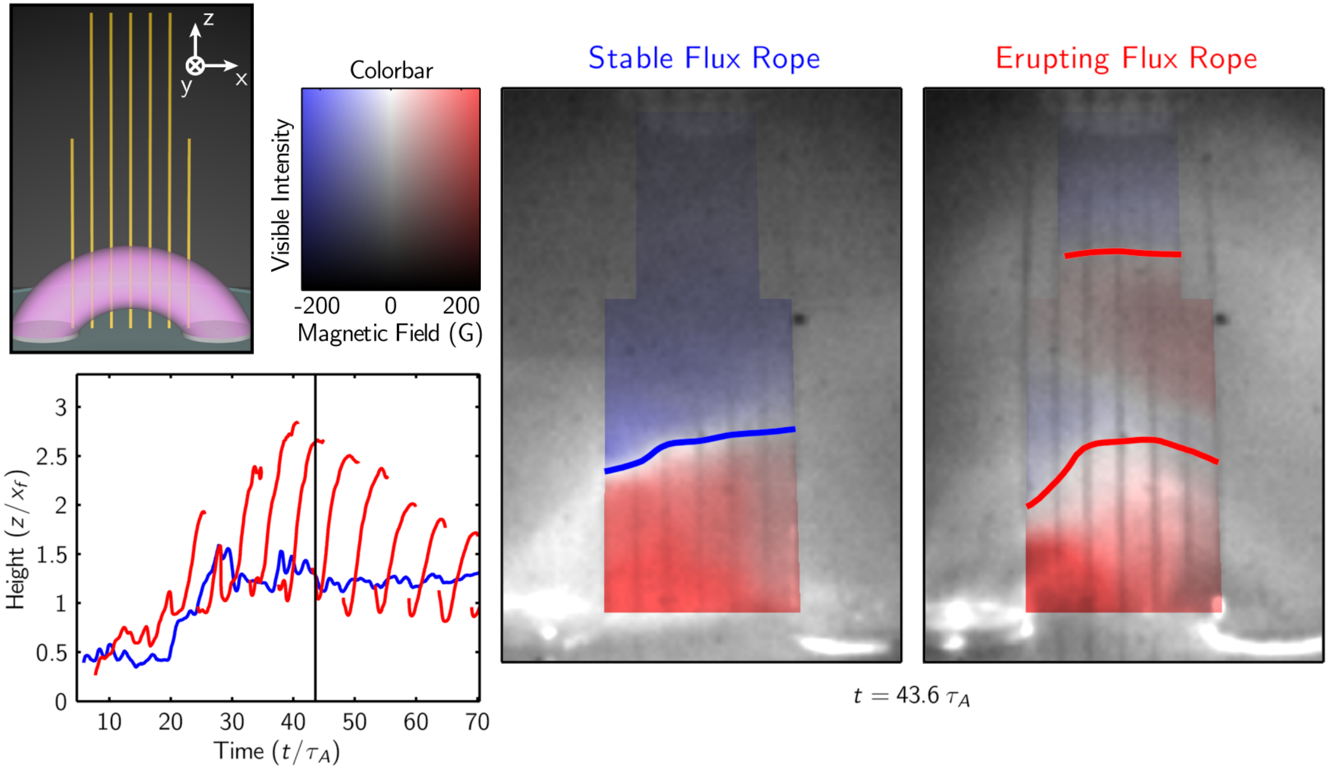


Magnetic probe diagnostic array

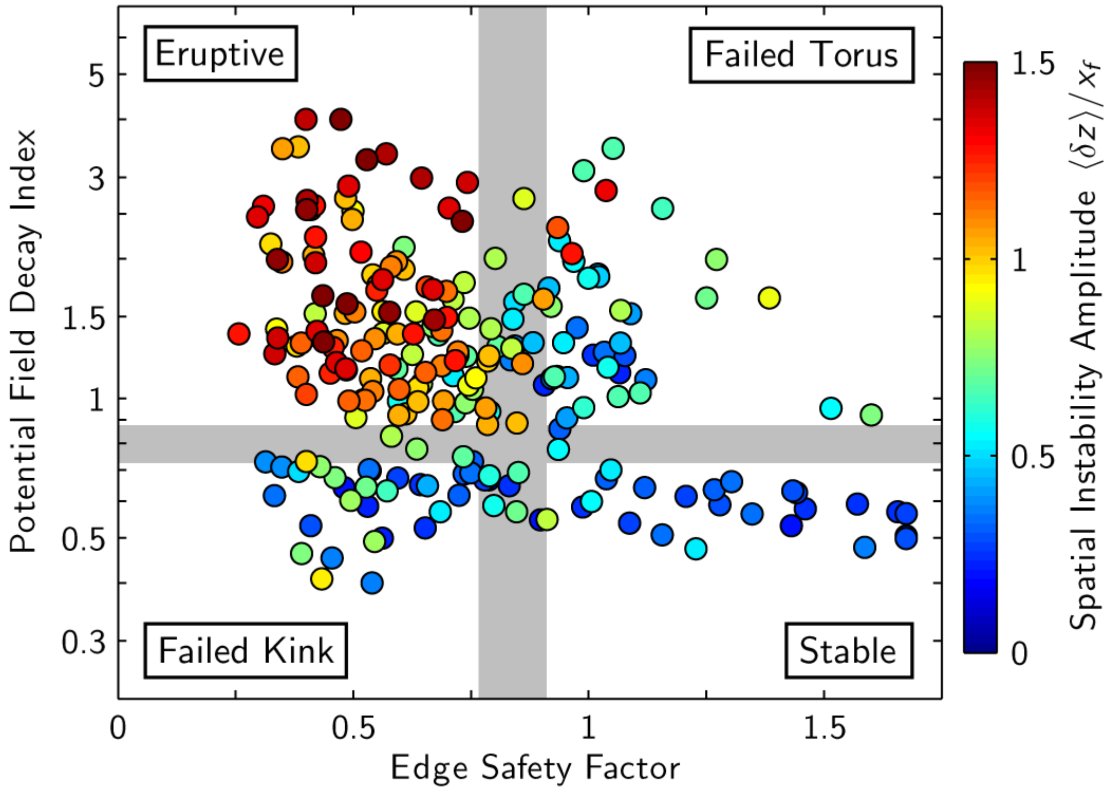




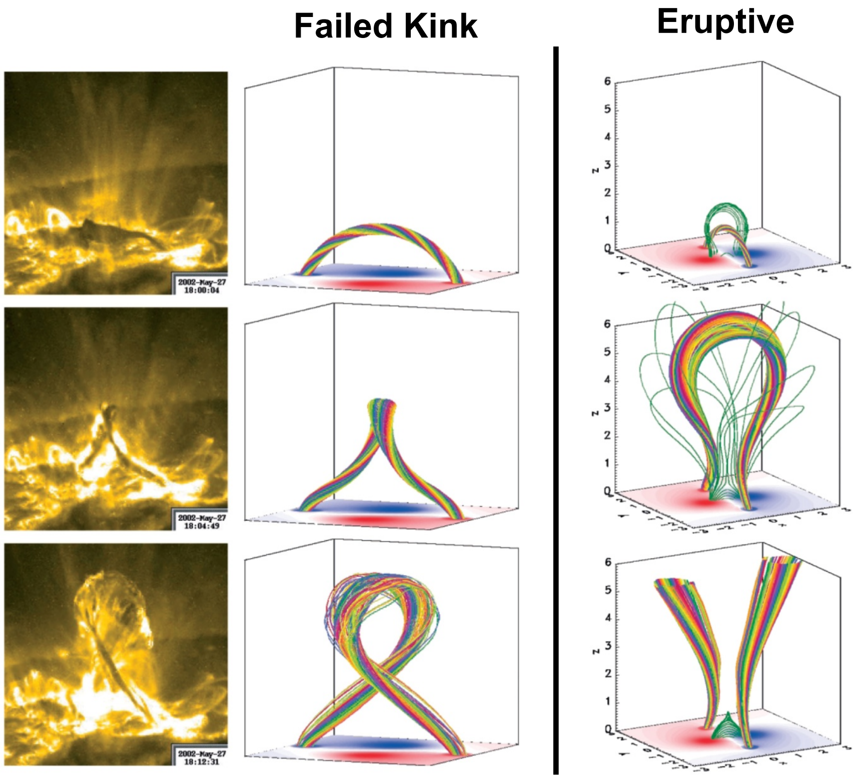
Both stable and erupting flux ropes are produced



The measured torus vs. kink instability parameter space



The failed kink regime is consistent with previous work



Török & Kliem, *ApJ*, 2005

- Török & Kliem (2005), Fan et al. (2007), etc., have shown that low field decay index leads to failed kink events
- What about the experimentally observed *n* ~ 0.8 threshold?
  - The "partial torus instability" → the line-tied geometry amplifies the hoop force [Olmedo & Zhang 2010]
  - The series inductance of the laboratory capacitor bank
- The solar torus criterion is therefore likely somewhere between *n* = 0.8 and 1.5

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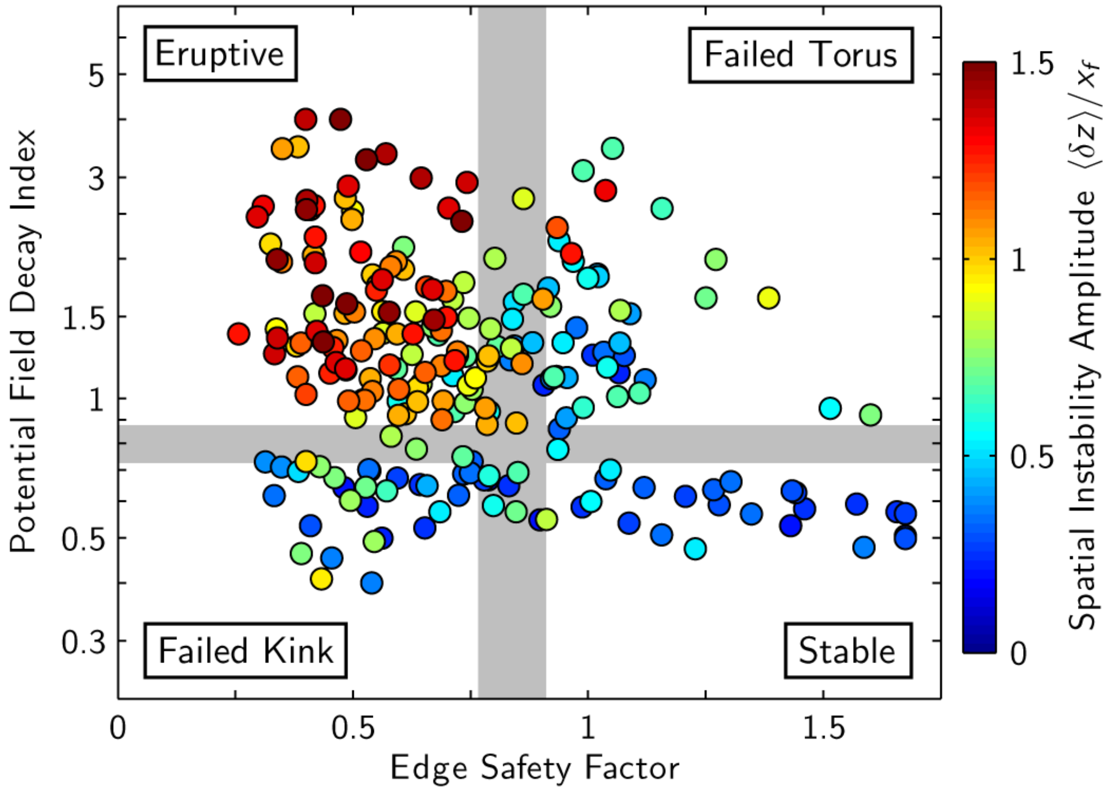
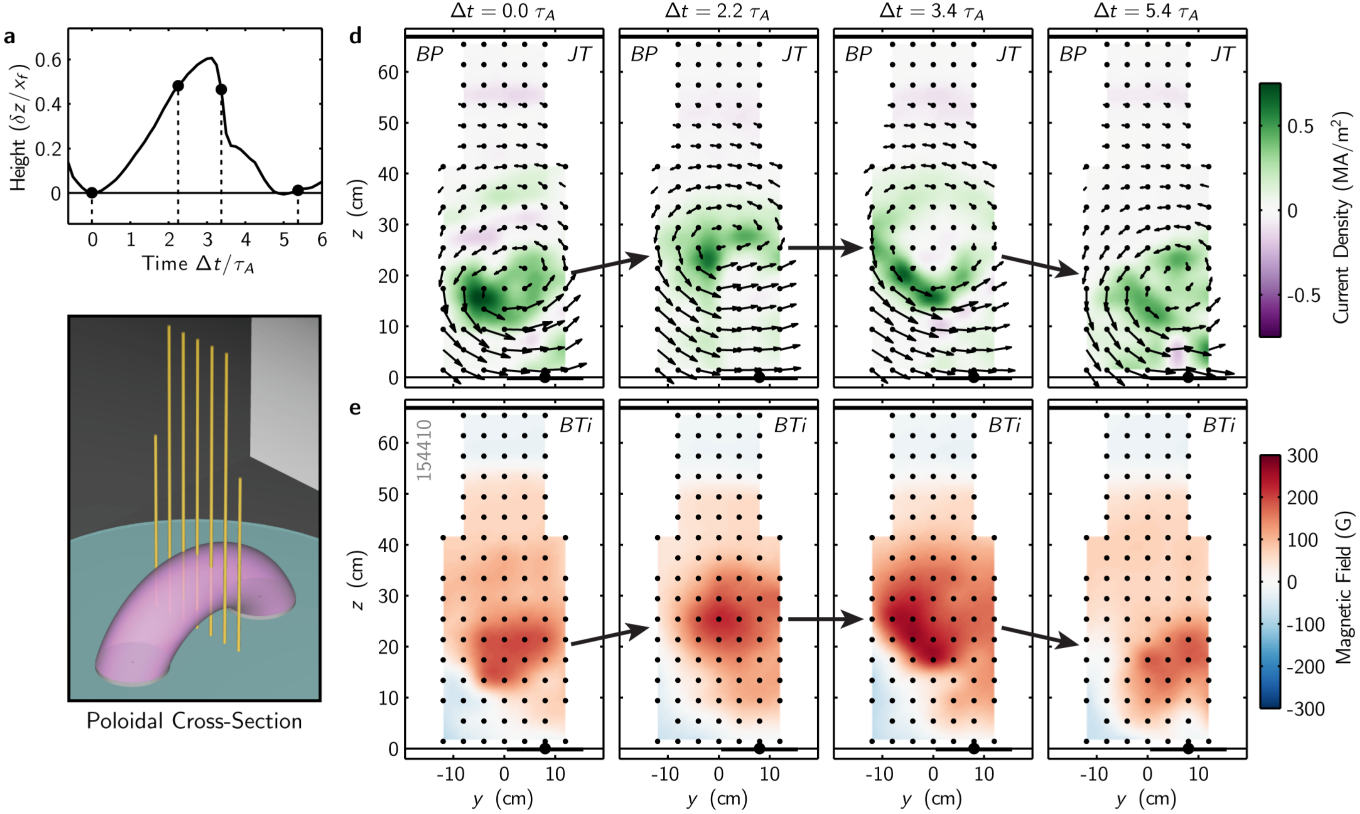
The failed torus regime → how to explain?



Failed torus vs. eruptive events



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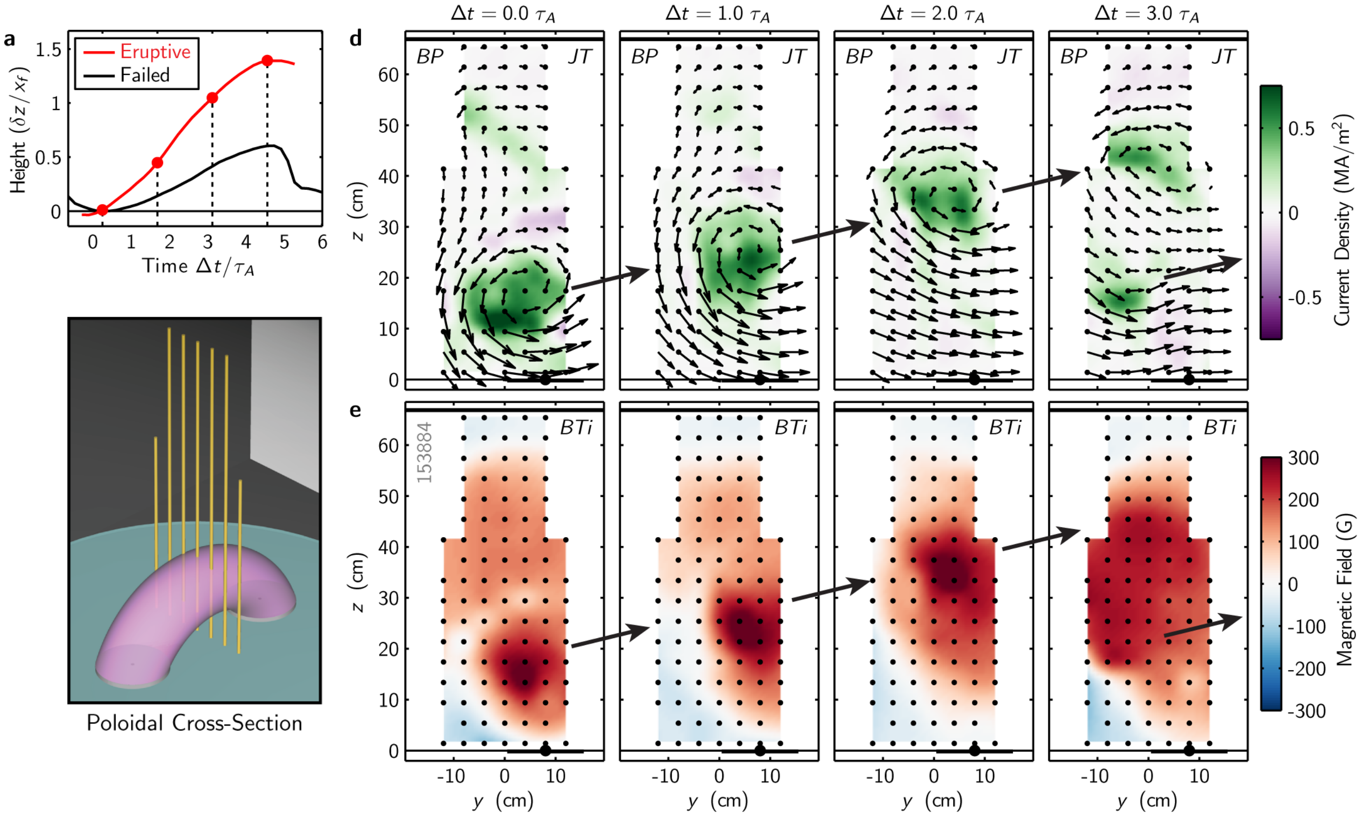

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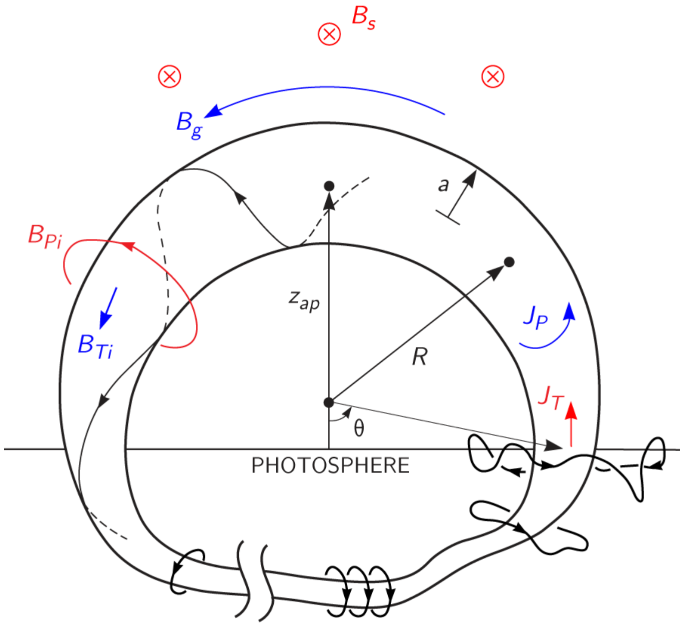


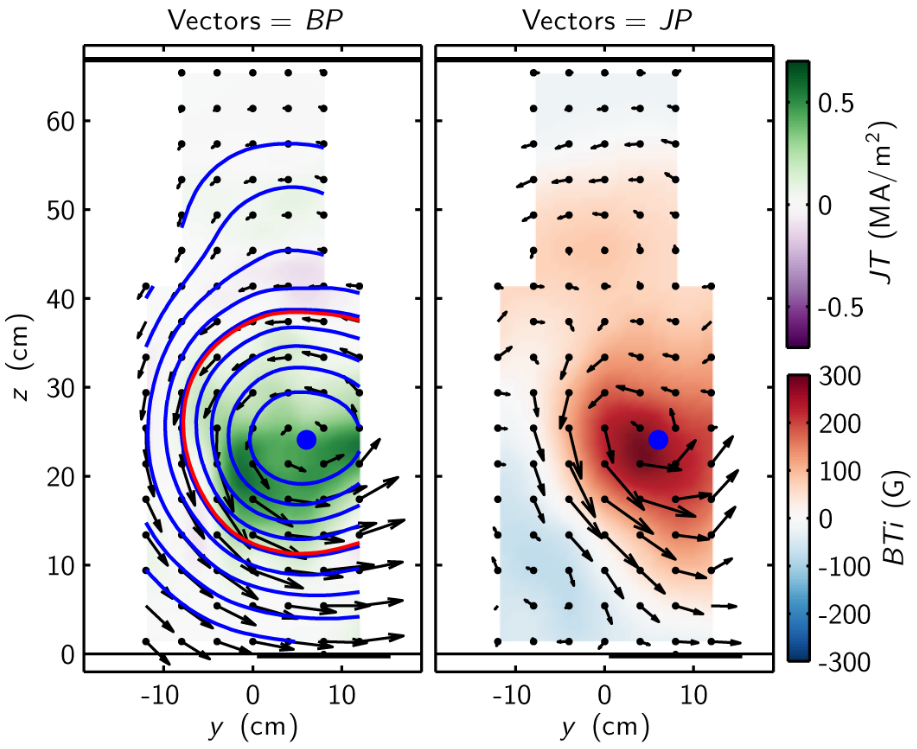
Adapted from J. Chen, *ApJ*, 1989, 2010

Measuring the forces at the flux rope apex

- Source terms:

  $$\mathbf{f} = \mathbf{J} \times \mathbf{B}$$

- **B** and J_T are straightforwardly measured
- Local toroidal symmetry → $\mathbf{J}_P$
- Compute a local poloidal flux function
- Minor radius → 90% of toroidal current enclosed



Measuring the forces at the flux rope apex

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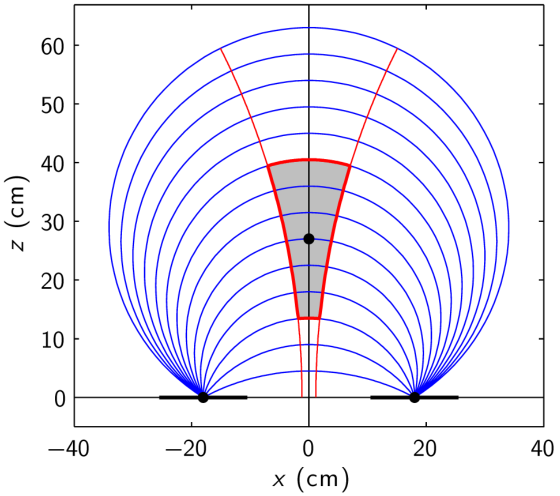
Integrate over the “apex wedge” of the rope:

$$F_i = \frac{1}{R_0} \int_0^{2\pi} d\theta \int_0^{a} dr \left[r\, h_T(z)\, f_i(r, \theta) \right]$$



$F_i \equiv$ force per unit length

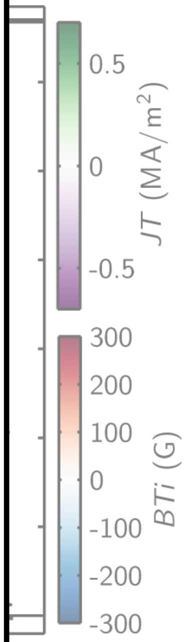
$R_0 \equiv$ major radius

$\theta \equiv$ poloidal angle

$r \equiv$ minor radius coordinate

$a \equiv$ minor radius

$h_T \equiv$ curvilinear scale factor



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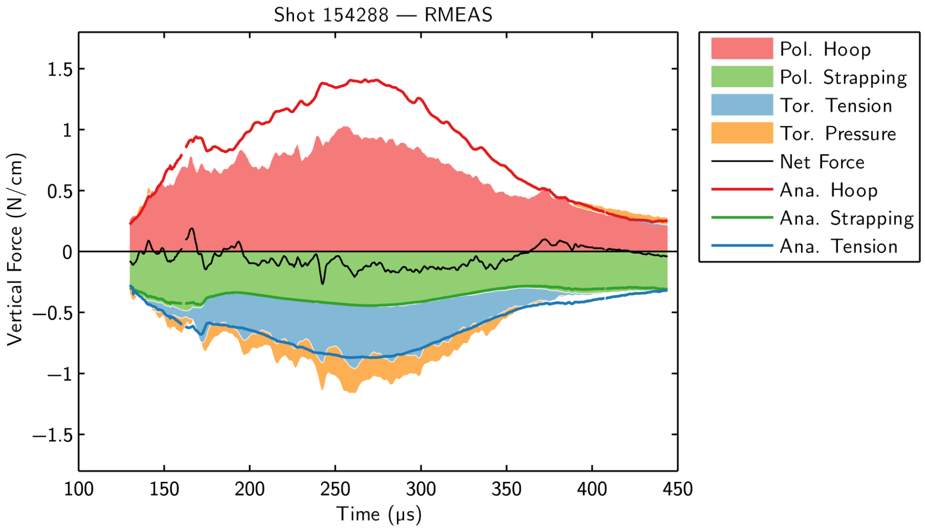
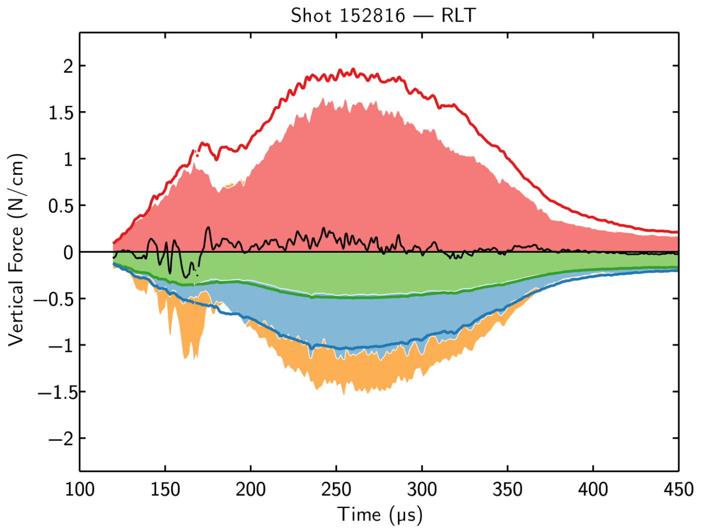
Verification of low-β equilibrium force balance

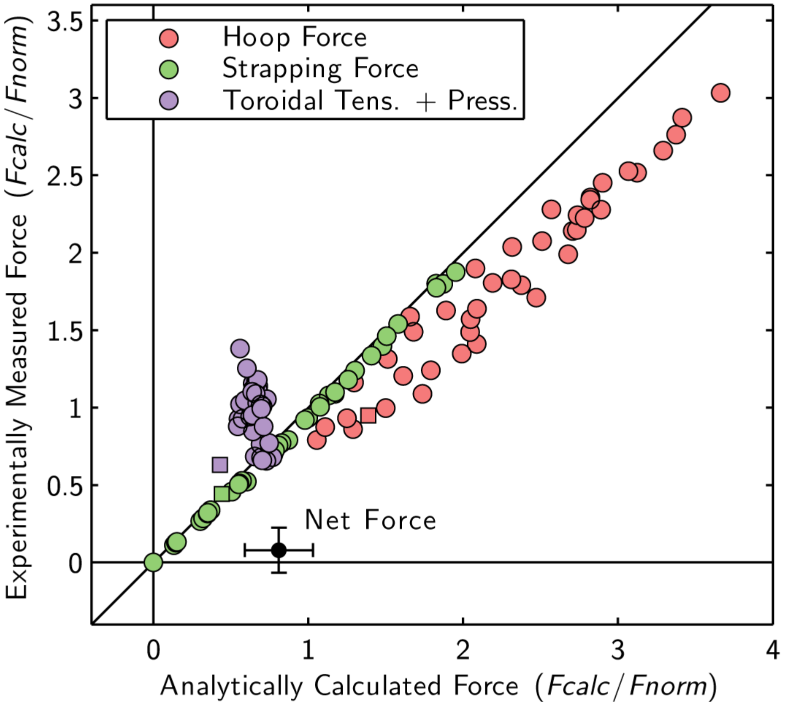




- Weaker-than-expected hoop force
- Excellent agreement for the strapping force
- Significant contributions from toroidal field tension and toroidal field pressure

- Net force ~ 0 in each case → low β, force-free equilibrium

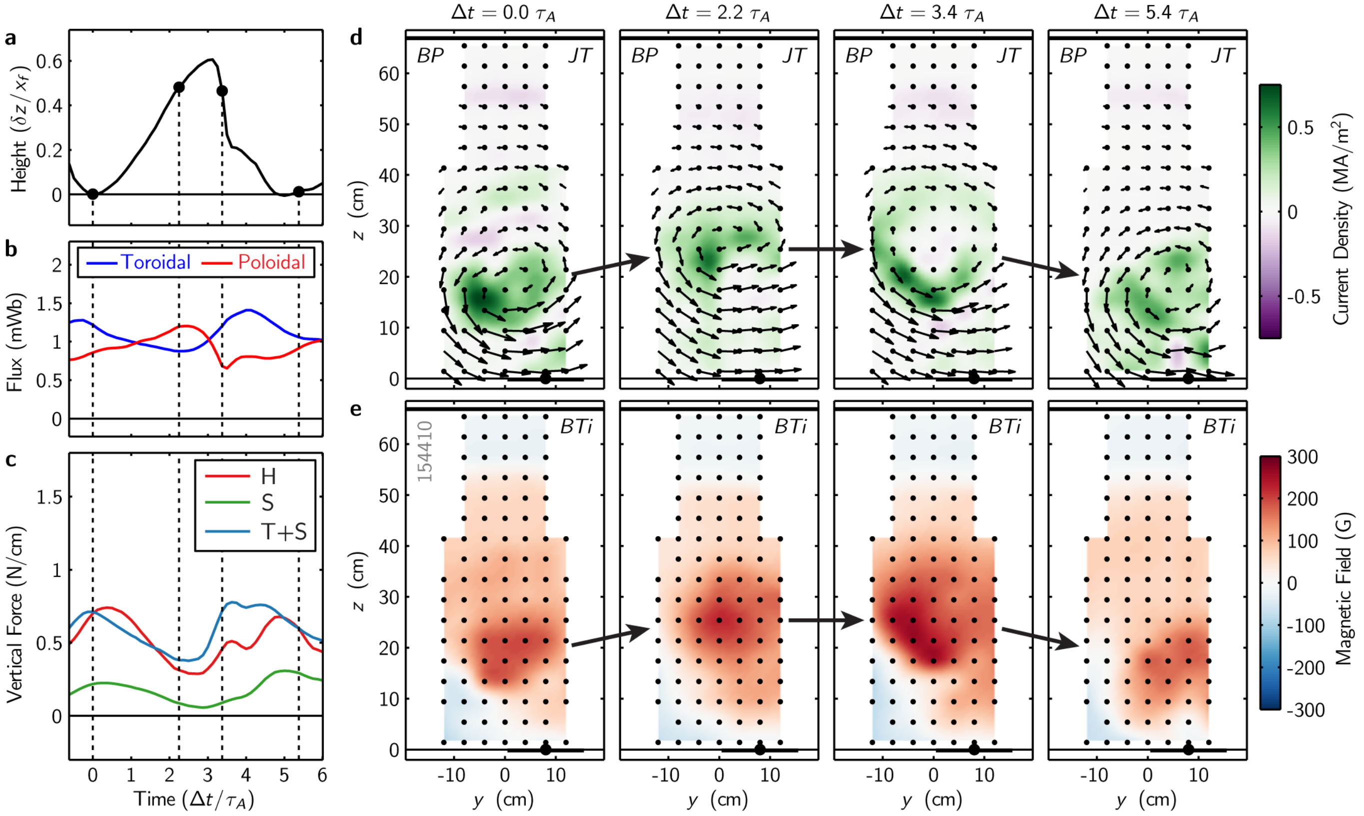
Measured forces vs. analytical predictions



$$F_{norm} = \frac{\mu_0 I_T^2}{4\pi x_f}$$

- Force-free equilibria are measured throughout the parameter space
- Validates the force analysis and the low-β assumption
- Corrections:
  - Weaker hoop force
  - Stronger toroidal field tension + toroidal field pressure
- Both corrections promote confinement

Failed torus vs. eruptive events



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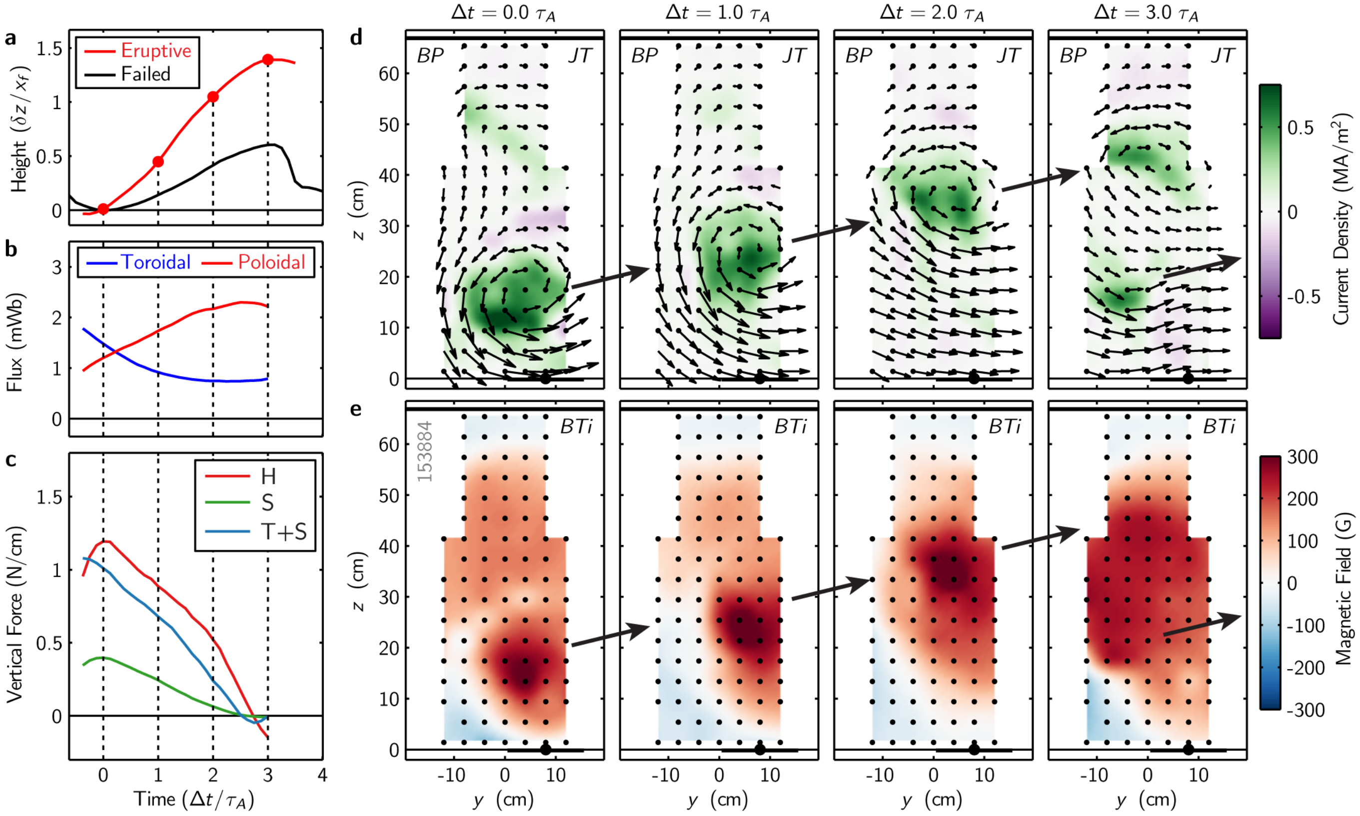


Summary

- **The torus vs. kink instability parameter space:**
  - Verification of the "traditional" torus instability

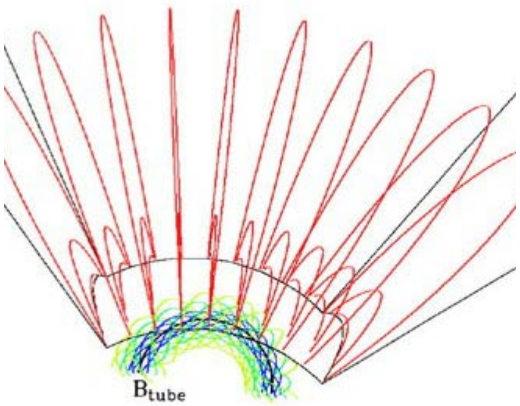
    → Failed kink and eruptive regimes
  - Discovery of the failed torus regime
- **The toroidal field tension force:**
  - A dynamic "self-organization" event generates a strong toroidal field tension force that causes the eruption to fail
  - The flux rope is able to find a lower energy state through internal reconfiguration rather than external eruption
  - This new failed eruption mechanism lies outside of the "strapping force paradigm" → How does this translate to the corona?

Implications for solar observations and modeling

Can we find and study failed torus physics in numerical models?

- Failed torus events are *dynamic*:
  - Time-resolved modeling required
  - This limits the effectiveness of Nonlinear Force-Free Field (NLFFF) modeling
  - A relatively idealized approach could still be useful (e.g., Y. Fan et al.)

- Self-organization brings in new physics:
  - Flux conversion → reconnection (3D, small scale?)
  - What is the self-organization onset criterion?

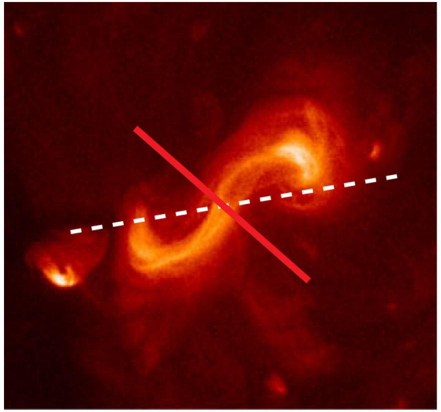


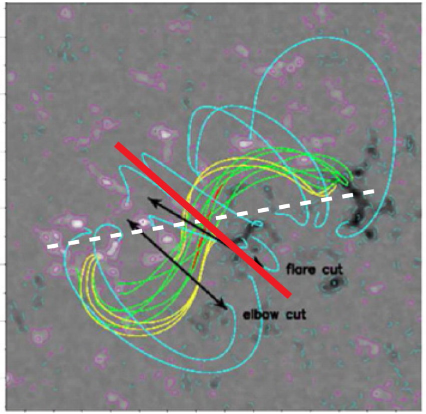
Y. Fan et al., *ApJ*, 2007

Implications for solar observations and modeling

Could there be a direct impact on observations and eruption prediction?

- The strong toroidal field tension force is derived from *vacuum guide field*
  - Weak tension force exists without guide field, but the strong, dynamic version requires external guide field
- From observations (or data-driven modeling), determine if there is significant guide field in a given active region → reduced probability of eruption





A. Savcheva et al., *ApJ*, 2012